Progress Report

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"An Investigation of the Origin, Age, and Composition of Meteorites"

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I. Publications

*1. Search for Optical Activity in the Orgueil Meteorite, R. Hayatsu, Science 149, 443-447 (1965).

*2. Fragmentation History of Asteroids, E. Anders, Icarus 4, 399-408 (1965).

*3. Cosmogenic and Radiogenic He, Ne, and Ar in Amphoteric Chondrites, J. of Geophys. Res. 70, 3735-3743 (1965).

*4. S^{34}/S^{32} Ratios for the Different Forms of Sulphur in the Orgueil Meteorite and their Mode of Formation, J. Monster, E. Anders, and H. Thode, Geochim. et Cosmochim. Acta 29, 773-779 (1965).

*5. Organic Compounds in Carbonaceous Chondrites, M.H. Studier, R. Hayatsu, and E. Anders, Science 149, 1455-1459 (1965).

*6. Age of Craters on Mars, E. Anders and J.R. Arnold, Science 149, 1494-1496 (1965).

*7. Metal Grains in Chondritic Meteorites, Submitted to Nature, October, 1965, 7 pages.

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*Preprints or reprints have been submitted to Technical Reports Officer prior to date of this report.

[redacted]

8. Rare Gas Isotopes in the Burşa and Cannakale Chondrites, Dieter Heymann, Submitted to Scientific Reports of the Faculty of Science, Ege University, Izmir, Turkey, November, 1965, 4 pages.

II. Talks at Scientific Meetings

1. "Chondrites" (J.A. Wood). Gordon Conference on the Chemistry and Physics of Space, Tilton, New Hampshire, June 28, 1965.

2. "Meteorite Parent Bodies" (E. Anders). Gordon Conference on the Chemistry and Physics of Space, Tilton, New Hampshire, June 28, 1965.

3. "Correlation between impact-shock effects and preatmospheric depth in crater-forming meteorites". (M.E. Lipschutz) 20th IUPAC Congress, Moscow, USSR, July 13, 1965.

4. "Organic Compounds in Carbonaceous Chondrites" (R. Hayatsu) 20th IUPAC Congress, Moscow, USSR, July 13, 1965.

5. "Trace element fractionations in meteorites" (E. Anders) 20th IUPAC Congress, Moscow, USSR, July 14, 1965.

6. "Ages and U-Content of some hypersthene chondrites" (D. Heymann) 20th IUPAC Congress, Moscow, USSR, July 15, 1965.

7. "Comets" (J. A. Wood) July 1965, Space Science Board, NAS Summer Study, Woods Hole, Mass.

8. "Origin of Organic Compounds in Carbonaceous Chondrites" (E. Anders) October 12, 1965. National Academy of Sciences, Seattle, Washington.

II. Work in Progress

1. Age of Meteorites.

(Dieter Heymann and Agatha Fris)

The mass spectrometer was damaged during the installation of a new air conditioning system. We took advantage of this enforced shutdown to make many mechanical changes in the instrument and associated components. However, the total down-time of the instrument exceeded four months.

A preliminary study was made of rare gases in a number of "pigeonite" or "disequilibrium" chondrites. It was found that these meteorites have considerable amounts of heavy primordial rare gases (planetary or fractionated type). The amounts of Ar^{36} are similar to those found in carbonaceous chondrites. This results seems consistent with the unequilibrated state of the major silicate minerals in these chondrites.

(Black chondrites) Rare gas studies of black hypersthene chondrites were completed. Nine of these meteorites have U-He ages of about 500 m.y., indicating a major outgassing event of hypersthene chondrites at that time. The rare gas work was supplemented with metallographic and X-ray studies. It was found that black hypersthene chondrites are replete with reheating and shock effects. In most of these, the metal was apparently heated into the taenite field. On cooling it transformed to martensitic nickel-iron (α_2, distorted b. c. c.) or polycrystalline kamacite, depending on nickel content. All the strongly reheated chondrites show evidence of local or widespread melting of FeS. The Laue patterns of olivine show evidence of moderate shock (preferred orientation) or strong shock (random orientation, smooth rings). X-ray patterns of 32 hypersthene chondrites, including black as well as veined and brecciated chondrites show that there is a strong correlation between shock-effect (grading from spot patterns to preferred orientation to smooth rings) and U-He ages. Our results are consistent with the hypothesis that most hypersthene chondrites suffered reheating after the major metamorphic heating about 4.5 b.y. ago; that the reheating was caused by shock; that the number of collisions (of the parent body) involved was relatively small, perhaps three or four; and that the largest of these collisions took place about 500 m.y. ago.

U-He and K-Ar ages were determined for nine hypersthene chondrites of olivine composition Fa_{26} in an attempt to establish whether the apparent age-difference between amphoterites and hypersthene chondrites was real or false. The former had been shown by us to have systematically higher ages. Our results seem to suggest that amphoterites are a distinct subclass of ordinary chondrites that was not involved in the 500 m.y. collision which affected the hypersthene chondrites.

2. Meteorite Orbits

Arnold's computer program has been used to estimate relative crater formation grequencies on Mars and the Moon (Paper 6). These data suggest that the Martian surface features are younger than had been previously supposed.

The program was modified to permit a step-by-step examination of the orbital changes. It appears that interactions with Jupiter are not treated realistically, and that the model contains a built-in bias against large, eccentric orbits. We are attempting to correct these deficiencies at present.

In spite of this defect, the present program was used to generate meteorite orbits from two classes of potential parent bodies: not considered by Arnold: Mars-crossing and Earth-crossing (Apollo) asteroids. It turns out that the Apollo asteroids, alone among all classes, give a satisfactory match with both the age and velocity distribution of meteorites. Mars asteroids match velocities but not ages; the Moon, ages but not velocities; and the ring asteroids, neither. With the improved computer program, these calculations may well yield highly significant clues to the origin of meteorites.

3. Prebiological Organic Matter

(Ryoichi Hayatsu, Martin H. Studier, and Atsuko Oda)

We had previously shown (Paper 5) that the trapped volatiles in carbonaceous chondrites grossly resembled an equilibrium distribution in a carbon-rich C-H-O mixture. We therefore proposed that the organic compounds in meteorites formed in the solar nebula under near-equilibrium chonditions, during rapid cooling of a gas phase depleted in hydrogen.

In an experimental test of this hypothesis, we found that stony and iron meteorites catalyze the reaction between CO and H_2, the principal constituents of a hot cosmic gas. Even in hydrogen-rich mixtures approaching cosmic composition, aliphatic and aromatic hydrocarbons are produced in a matter of minutes at temperatures between 20°C and 580°C. When these hydrocarbons are partially equilibrated by sustained reheating, they match the hydrocarbon distribution in carbonaceous chondrites in all important respects. A manuscript describing this work is in preparation.

2. Origin of Meteorites

(John A. Wood and Betty Nielsen)

The paper on the metal phase in chondrites is presently being typed. The abstract follows:

"Metal grains in 34 chondrites were studied microscopically and by electron microprobe analysis. Taenite and kamacite crystals in ordinary, unequilibrated ordinary, and type III carbonaceous chondrites exhibit the same compositional inhomogeneities previously observed in octahedrites. It is shown that the metal grains evolved *in situ* to their present form during cooling from metamorphic temperature. Correlations exist between the dimension and central Ni content of taenite and kamacite crystals in many chondrites, making it possible to deduce the rates at which the chondrites cooled by the same technique previously applied to octahedrites. Ordinary chondrites cooled through 500°C at 1-10°/million years, the other types noted above at 0.2-0.6°/m.y. Heat flow calculations show that these cooling rates would have obtained in sites respectively 20-150 km deep in planets of ≥90 km radius, and 60-200 km deep in ≥200 km radius planets. Some of the processes that would have occurred during metamorphism are discussed, especially losses of gas and certain trace elements.

Type II carbonaceous chondrites appear to contain no high-Ni metal grains. Their properties are consistent with the theory that they represent unmetamorphosed primordial planetary matter. Distinct differences are shown to exist between metal grains in the light and dark components of Pantar-type (gas-rich) chondrites, evidence that they evolved in widely separated sites. Several chondrites that appear to have been reheated (as for example by shock compression during interplanetary collisions) are described, and the metallographic changes wrought by various degrees of reheating are noted. A model for chondrite formation and evolution that embraces all these effects is presented (Sec. 7)."